EXPECTED BEHAVIOUR OF DIFFERENT SEMICONDUCTOR MATERIALS IN HADRON FIELDS

I.Lazanu [a], S.Lazanu [b] and M.Bruzzi [c]

[a] *University of Bucharest, Faculty of Physics, P.O.Box MG-11, Bucharest-Magurele, Romania, electronic address: ilaz@scut.fizica.unibuc.ro*

[b] *National Institute for Materials Physics, P.O.Box MG-7, Bucharest-Magurele, Romania, electronic address: lazanu@alpha1.infim.ro*

[c] *Universita di Firenze, Dipartimento di Energetica, Via S. Marta 3, 50139 Firenze, Italy, electronic address: bruzzi@fi.infn.it*

Abstract

The utilisation of semiconductor materials as detectors and devices operating in high radiation environments, at the future particle colliders, in space applications or in medicine and industry, necessitates to obtain radiation harder materials. A systematic theoretical study has been performed, investigating the interaction of charged hadrons with semiconductor materials and the mechanisms of defect creation by irradiation. The mechanisms of the primary interaction of the hadron with the nucleus of the semiconductor lattice have been explicitly modelled and the Lindhard theory of the partition between ionisation and displacements has been considered. The behaviour of silicon, diamond, and some $A^{III}B^{V}$ compounds, as GaAs, GaP, InP, InAs, InSb has been investigated. The nuclear energy loss, and the concentration of primary defects induced in the material bulk by the unit hadron fluence have been calculated. The peculiarities of the proton and pion interactions as well as the specific properties of the semiconductor material have been put in evidence.

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Key words: hadrons, radiation damage, diamond, silicon, $A^{III}B^{V}$ semiconductors

1 Introduction

The crystalline materials for semiconductor devices used in high fluences of particles are strongly affected by the effects of radiation. After the interaction between the incoming particle and the target, mainly two classes of degradation effects are observed: surface and bulk material damage, due to the displacement of atoms from their sites in the lattice. For electrons and gammas the effects are dominantly at the surface, while the heavy particles (pions, protons, neutrons, ions) produce both types of damages.

Up to now, in spite of the experimental and theoretical efforts, the problems related to the behaviour of the semiconductor materials in radiation fields, the identification of the induced defects and their characterisation, as well as the explanation of the degradation mechanisms are still open problems.

The utilisation of semiconductor materials as detectors and devices operating in high radiation environments, at the future particle colliders, in space applications, in medicine and industry, makes necessary to obtain radiation harder materials.

The diamond and different $A^{III}B^{V}$ compounds (GaAs, GaP, InP, InAs, InSb) are in principle, possible competitors for silicon to different electronic devices. In the present paper a systematic theoretical study of the expected behaviour of these semiconductor materials in hadron fields (protons and pions) is presented.

All analysed materials have a zinc-blend crystalline structure. Silicon is at the base of electronic industry, diamond and the $A^{III}B^{V}$ compounds present attractive electrical and/or luminescence properties [1], of interest for different applications.

2 Interaction of charged hadrons with semiconductor materials and mechanisms of defect creation by irradition

The charged particles interact with both atomic and electronic systems in a solid. The total rate of energy loss, as a function of distance, is called the stopping power. This one could, in general, be divided artificially into two components, the nuclear and the electronic part:

$$\left(-\frac{dE}{dx}\right)_{total} = \left(-\frac{dE}{dx}\right)_{nuclear} + \left(-\frac{dE}{dx}\right)_{electronic}$$

Roughly speaking, the energy lost due to interactions with electrons gives rise to material ionisation, while the energy lost in interactions with nuclei is to

the origin of defect creation.

A comprehensive theoretical treatment of electronic stopping which covers all energies of interest cannot be formulated simply because of different approximations concerning both the scattering and contribution of different electrons in the solid. For fast particles with velocities higher then the orbital velocities of the electron, the Bethe-Bloch formula is to be used [2]. At lower velocities, inner electrons have velocities greater than particle velocity, and therefore do not contribute to the energy loss. This regime was modelled by Lindhard and Scharff [3].

If the particle has a positive charge, and a velocity close to the orbital velocity of its outer electrons, it has a high probability of capturing an electron from one of the atoms of the medium through which it passes. This process contributes to the total inelastic energy loss since the moving ion has to expend energy in the removal of the electrons which it captures.

The nuclear stopping depends on the detailed nature of the atomic scattering, and this in turn depends intimately on the form of the interaction potential. At low energies, a realistic potential based on the Thomas-Fermi approximation was used in the literature [3] and at higher energies, where scattering results from the interaction of unscreened nuclei, a Rutherford collision model is to be used.

In Figure 1, the nuclear stopping power calculated for protons and pions in diamond, silicon and GaAs is represented, as a function of the kinetic energy of the particle. The nuclear stopping power is greater for heavier incident particles (protons compared with pions), and for lighter media (diamond in comparison with silicon and GaAs). The position of its maximum is the same for protons and pions in the same medium.

The process of partitioning the energy of the recoil nuclei (produced due the interaction of the incident particle with the nucleus, placed in its lattice site) by new interaction processes, between electrons (ionisation) and atomic motion (displacements) is considered in the frame of Lindhard theory [4].

The mechanism considered in the study of the interaction between the incoming particle and the solid, by which bulk defects are produced, is the following: the particle, heavier than the electron, with electrical charge or not, interacts with the electrons and with the nuclei of the crystalline lattice. The nuclear interaction produces the bulk defects. As a result of the interaction, depending on the energy and on the nature of the incident particle, one or more light particles are formed, and usually one or more heavy recoil nuclei. These nuclei have charge and mass numbers lower or at least equal with the medium. After this interaction process, the recoil nucleus or nuclei, if they have sufficient energy, are displaced from the lattice positions in interstitials. Thus, the primary

knock-on nucleus, if its energy is large enough, can produce the displacement of a new nucleus, and the process can continue as a cascade, until the energy of the nucleus becomes lower than the threshold for atomic displacements. Because of the regular nature of the crystalline lattice, the displacement energy is anisotropic. In the present model, averaged values for displacement energies have been considered. In the concrete evaluation of defect production, the nuclear interactions must be modelled, see for example [5–7]. The primary interaction between the hadron and the nucleus of the lattice presents characteristics reflecting the peculiarities of the hadron, especially at relatively low energies. If the inelastic process is initiated by nucleons, the identity of the incoming projectile is lost, and the creation of secondary particles is associated with energy exchanges which are of the order of MeV or larger. For pion nucleus processes, the absorption, the process by which the pion disappears as a real particle, is also possible.

The energy dependence of cross sections, for proton and pion interaction with the nucleus, present very different behaviours: the proton-nucleus cross sections decrease with the increase of the projectile energy, then have a minimum at relatively low energies, followed by a smooth increase, while the pion nucleus cross sections present for all processes a large maximum, at about 160 MeV, reflecting the resonant structure of interaction (the Δ_{33} resonance production), followed by other resonances, at higher energies, but with much less importance. Due to the multitude of open channels in these processes, some simplifying hypothesis have been done [8].

The physical quantity that characterise the primary defects is the concentration of primary radiation induced defects on the unit particle fluence (CPD) [6]. This quantity permits the correlation of damages produced in different materials at the same kinetic energy of the incident hadron. For the comparison of the effects of different particles in the same semiconductor material, the non ionising energy loss (NIEL) is useful.

3 Theoretical expected material behaviour

The behaviour of these materials in proton fields is characterised by the CPD. In Figure 2, the dependence of the CPD as a function of the protons kinetic energy and medium mass number (diamond, silicon, GaAs and InP) is presented - see references [5,9] and references cited therein. Low kinetic energy protons produce higher degradation in all materials.

For pion induced degradation, the energy dependence of CPD and NIEL presents two maxima, the relative importance of which depends on the target mass number: one in the region of the Δ_{33} resonance, more pronounced

for light elements and compounds containing light elements, and another one around 1 GeV kinetic energy, more pronounced for heavy elements. At higher energies, an weak energy dependence is observed, and a general dependence of the NIEL can be approximated [8,10]. In Figure 3a, the CPD for all these materials is represented as a function of the pion kinetic energy and of material average mass number.

These materials could be separated into two classes, the first with monoatomic materials or materials with relatively close mass numbers, and the second comprising binary materials with remote mass numbers of the elements. In Figures 3b and 3c respectively, the energy and mass number dependence of the CPD for the two groups of materials are represented separately.

A slow variation of the primary defect concentration has been found for pion irradiation of diamond, silicon, GaP and GaAs, in the whole energy range of interest, with less than 2 displacements/cm/unit of fluence. In contrast to this situation, GaP, InAs and InSb are characterised by a low CPD in the energy range up to 200 MeV, followed by a pronounced increase of displacement concentration, to more than 8 displacements/cm/unit of fluence at high energies.

4 Summary

A systematic theoretical study has been performed, investigating the interaction of charged hadrons with semiconductor materials and the mechanisms of defect creation by irradiation. The mechanisms of the primary interaction of the hadron with the semiconductor nucleus lattice have been explicitly modelled and the Lindhard theory of the partition between ionisation and displacements has been considered.

The nuclear stopping power is greater for heavier incident particles (protons compared with pions), and for lighter media (diamond in comparison with silicon and GaAs). The position of its maximum is the same for protons and pions in the same medium.

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get mass number: one in the region of the Δ_{33} resonance, more pronounced for light elements and compounds containing light elements, and another one around 1 GeV kinetic energy, more pronounced for heavy elements. At higher energies, an weak energy dependence is observed. A slow variation of the primary defect concentration has been found for pion irradiation of diamond, silicon, GaP and GaAs, in the whole energy range of interest, with less than 2 displacements/cm/unit of fluence. In contrast to this situation, GaP, InAs and InSb are characterised by a low CPD in the energy range up to 200 MeV, (which represent the energy range up to their utilisation in pion field is recommended), followed by a pronounced increase of displacement concentration to more than 8 displacements/cm/unit of fluence at high energies.

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Figure captions

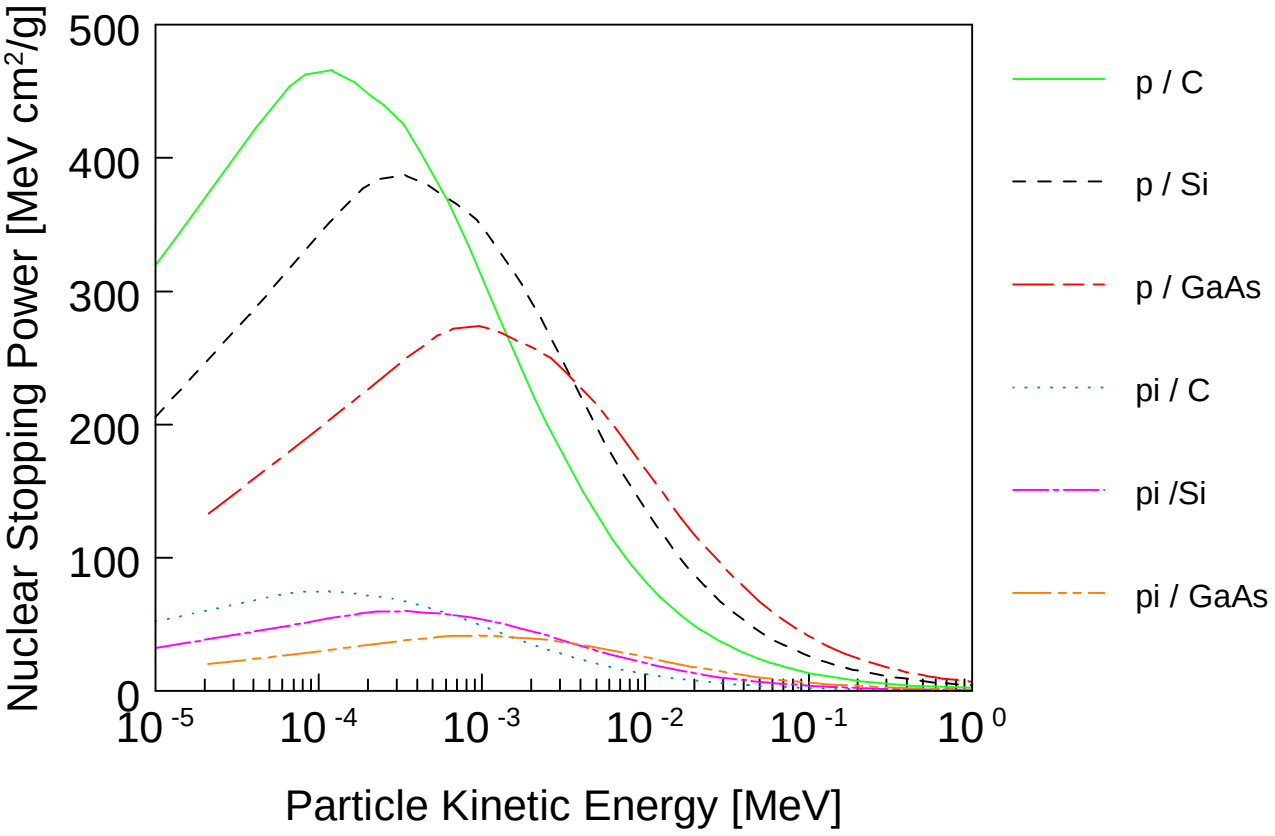
Figure 1: Nuclear stopping power of protons and pions in diamond, silicon and GaAs.

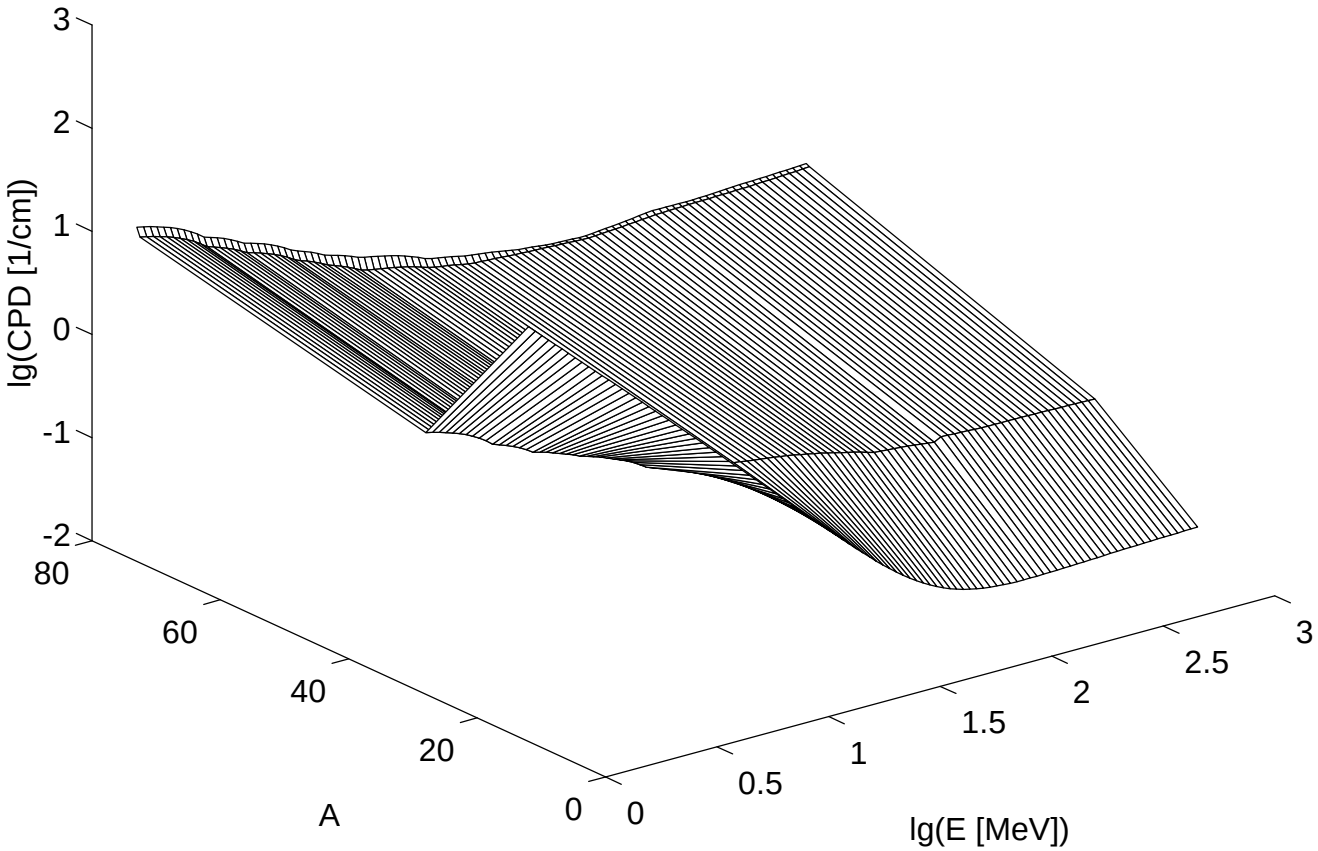
Figure 2: The concentration of primary induced defects for unit of fluence (CPD) in diamond, silicon, GaAs and InP by protons. The mesh surfaces are drawn only to guide the eye only. The discontinuity in the surface represent the behaviour. The data for proton - diamond are from [5], the silicon data are averaged values from [11] and [12], and that for GaAs and InP are from [12].

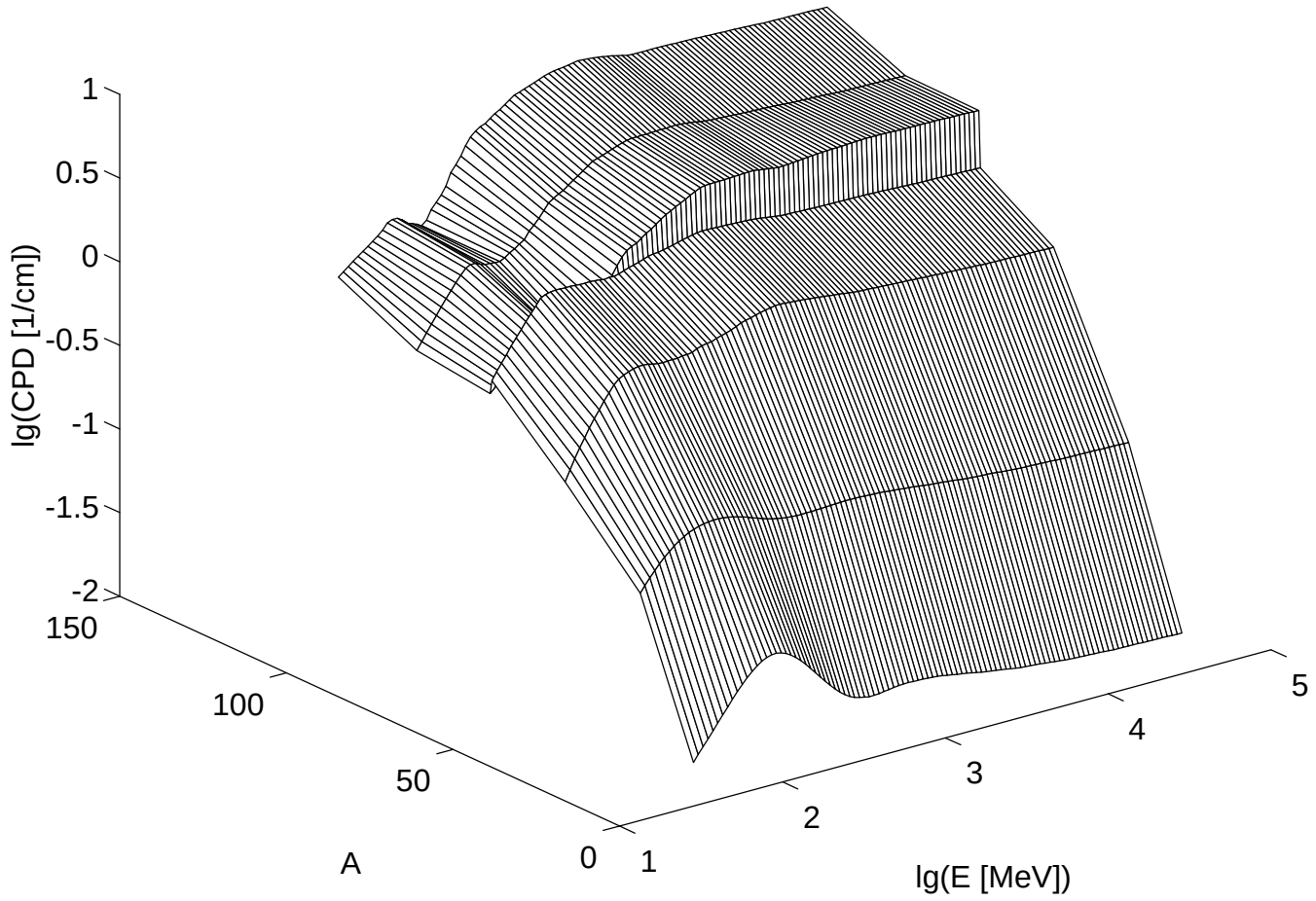
Figure 3a: The energy and material dependence of the concentration of primary defects on unit pion fluence in diamond, silicon, GaP, GaAs, InP, InAs and InSb. The mesh surfaces are plotted for guide the eyes. The differences in the behaviour of these materials are clearly suggested by the discontinuity in the mesh surface.

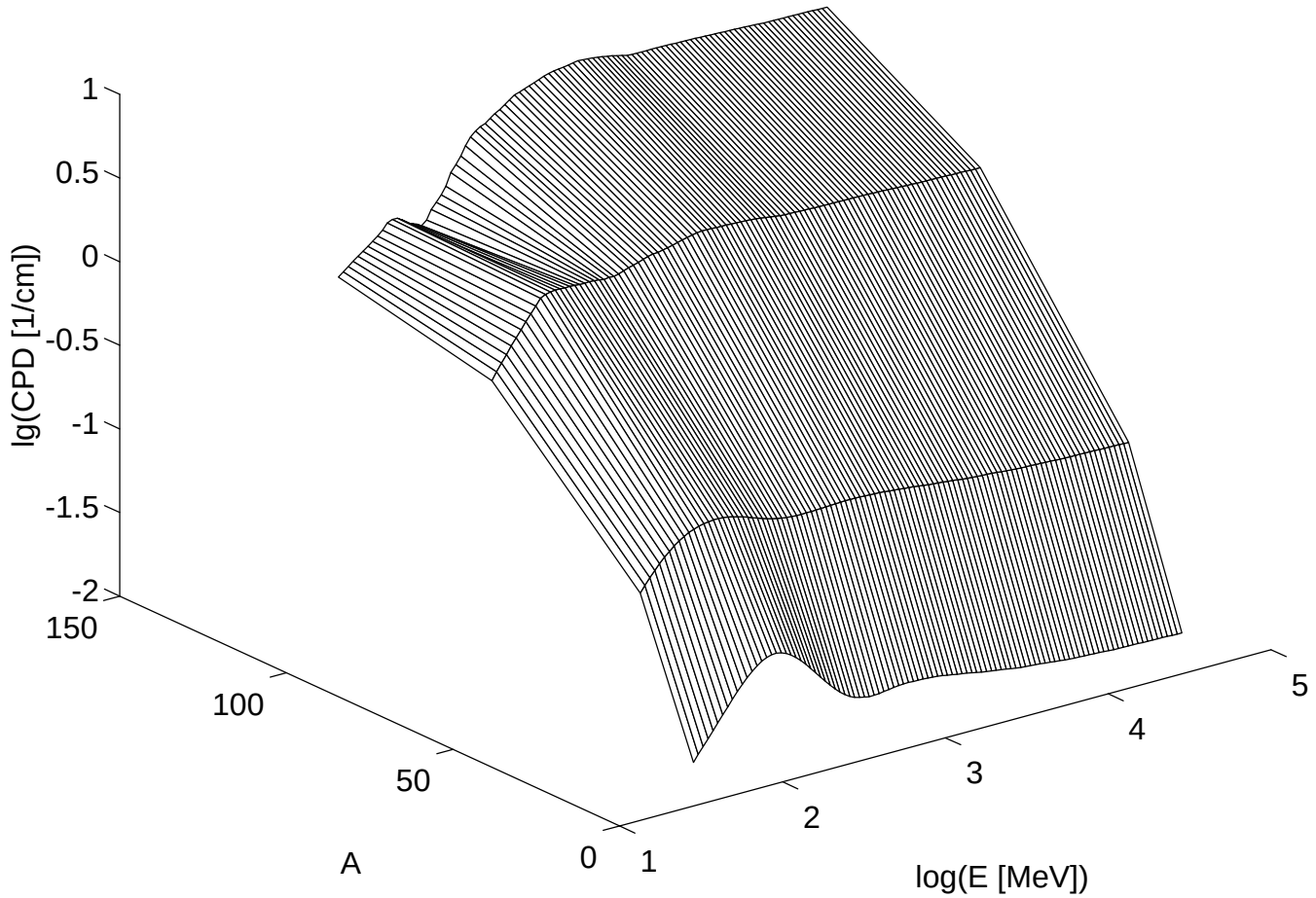
Figure 3b: The energy and material dependence of the concentration of primary defects on unit pion fluence, induced by pions in diamond, silicon, GaAs and InSb. The mesh surfaces are drawn to guide the eyes. A pronounced maximum, corresponding to the Δ_{33} resonance is clearly visible, and the second maximum at higher energies is important especially for InSb.

Figure 3c: The same as in Figure 3b, but for GaP, InP and InAs. The effects of the Δ_{33} resonance are less pronounced in respect to the effects of the inelastic region, at high energies.


Nuclear Stopping Power [MeV cm²/g]
500
400
300
200
100
0
10 -5
10 -4
10 -3
10 -2
10 -1
10 0
Particle Kinetic Energy [MeV]
p / C
p / Si
p / GaAs
pi / C
pi /Si
pi / GaAs


lg(CPD [1/cm])
3
2
1
0
-1
-2
80
60
40
20
0
A
0
0.5
1
1.5
2
2.5
3
lg(E [MeV])


1
0.5
0
-0.5
-1
-1.5
-2
lg(CPD [1/cm])
150
100
50
0
A
1
2
3
4
5
lg(E [MeV])


1
0.5
0
-0.5
-1
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-2
lg(CPD [1/cm])
150
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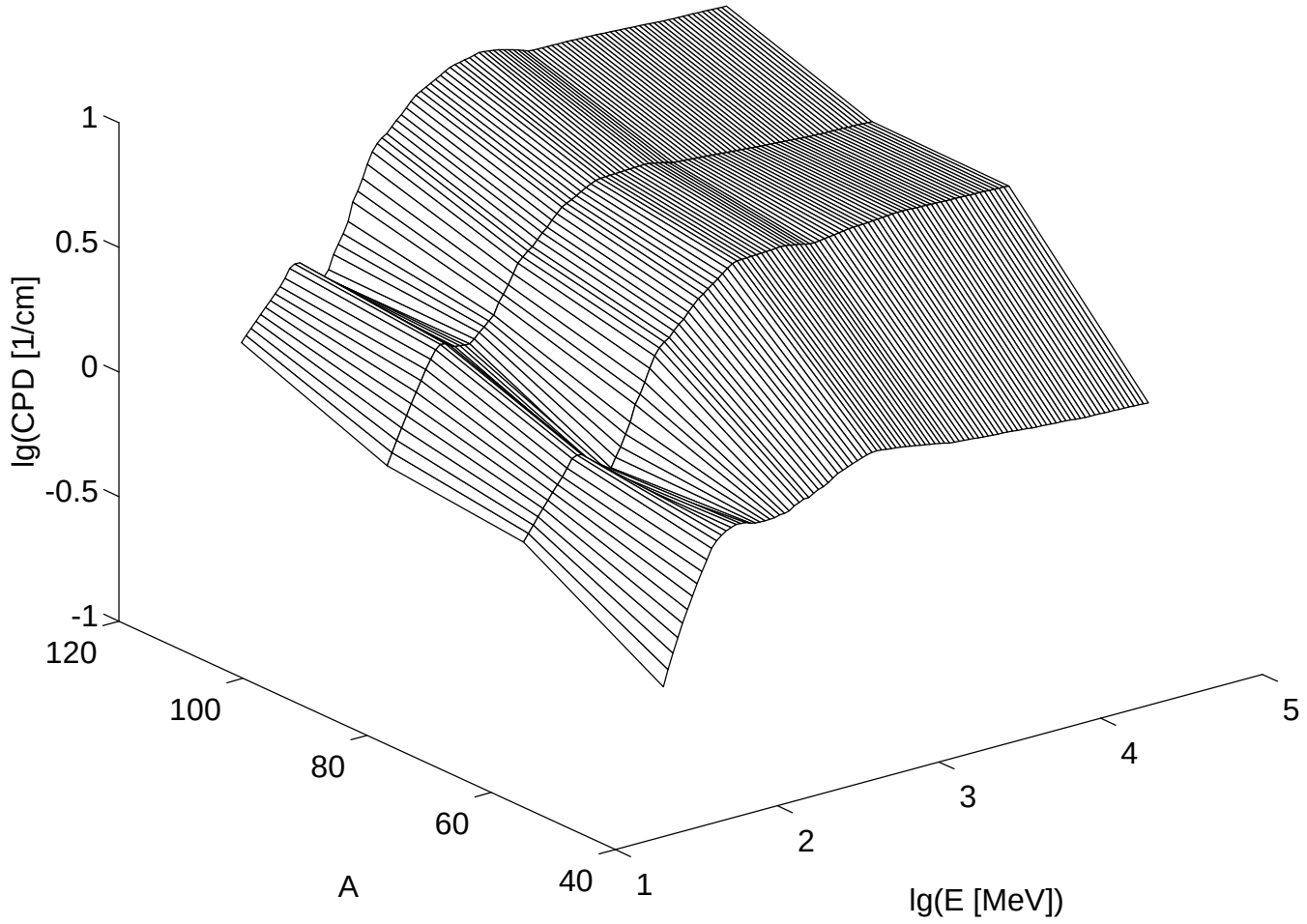
log(E [MeV])


1
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0
-0.5
-1
lg(CPD [1/cm])
120
100
80
60
40
A
1
2
3
4
5
lg(E [MeV])